



Atomic Energy
Control Board

P.O. Box 1046
Ottawa, Canada
K1P 5S9

Commission de contrôle
de l'énergie atomique

C.P. 1046
Ottawa, Canada
K1P 5S9

INFO-0189

NEUTRON DOSIMETRY FOR OIL-WELL LOGGING
OPERATIONS: AN INTERCOMPARISON OF NTA
AND CR-39 DOSIMETERS

by

W.G. Cross and A. Arneja
Atomic Energy of Canada Limited

A research report prepared for the
Atomic Energy Control Board
Ottawa, Canada

April 1986

86-05423/

NEUTRON DOSIMETRY FOR OIL-WELL
LOGGING OPERATIONS: AN INTER-
COMPARISON OF NTA AND CR-39 DOSIMETERS

A research report prepared for the Atomic Energy Control Board by W.G. Cross and A. Arneja, Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories.

ABSTRACT

Neutron doses recorded by NTA emulsion dosimeters and CR-39 damage track dosimeters, for a small, selected group of workers in the oil-well logging industry, have been compared over a one-year period. The same individuals wore NTA dosimeters for the normal one-month periods and CR-39 dosimeters for various periods from a month to a year. The results show that these workers often receive monthly dose equivalents between 30 μSv^* and the practical lower level of detectability (200 μSv) of the NTA dosimeters. However only 17% of the measured CR-39 dose equivalents totalled more than 1 mSv for the year, the maximum being 1.54 mSv. These dose equivalents are small compared with those received by many radiation workers in other industries.

* 1 Sv = 100 rem

RÉSUMÉ

Pendant un an, les doses de neutrons enregistrées par des dosimètres à émulsion NTA et par des dosimètres à traces de dommage CR-39 ont été comparées pour un petit groupe de travailleurs choisis de l'industrie de diagraphie des puits de pétrole. Ces individus ont porté des dosimètres NTA pendant une période normale d'un mois et des dosimètres CR-39 pour des périodes allant d'un mois à un an. Les résultats montrent que ces travailleurs reçoivent souvent des équivalents de dose mensuels allant de 30 μSv^* jusqu'à la limite minimale pratique de détection des dosimètres NTA (200 μSv). Cependant, pour une période d'un an, seulement 17 p. 100 des totaux des équivalents de dose enregistrés par les CR-39 ont excédé 1 mSv, le maximum étant de 1,54 mSv. Ces équivalents de dose sont petits on comparaison avec ceux reçus par plusieurs travailleurs sous rayonnements des autres industries.

* 1 Sv = 100 rem

DISCLAIMER

The Atomic Energy Control Board is not responsible for the accuracy of the statements made or opinions expressed in this publication and neither the Board nor the authors assume liability with respect to any damage or loss incurred as a result of the use made of the information contained in this publication.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	1
1. INTRODUCTION	1
2. CHARACTERISTICS OF RADIATION EXPOSURES IN OIL-WELL LOGGING	1
3. PROPERTIES OF NTA-EMULSION DOSIMETERS	3
3.1 Variation of response with energy	3
3.2 Angular dependence	3
3.3 Fading	4
3.4 Statistics of track counting	4
4. PROPERTIES OF CR-39 DAMAGE TRACK DOSIMETERS	5
4.1 Variation of response with energy	6
4.2 Angular dependence	6
4.3 Sensitivity and background	6
4.4 Fading of tracks	7
5. INTERCOMPARISON EXPERIMENT	8
6. RESULTS	9
7. DISCUSSION	9
8. CONCLUSIONS	9
TABLE	11
REFERENCES	12

1. INTRODUCTION

This report describes a field test to compare measurements of neutron doses received by workers in oil-well logging operations, as determined by two types of dosimeters - Kodak NTA track emulsions and CR-39 damage track detectors. The test was undertaken at the request of the Atomic Energy Control Board, because of difficulties in assessing the significance of very low readings obtained with NTA-emulsion dosimeters. Typical dose equivalents received by oil-well logging workers over one month periods appear to be close to, or below, the threshold of sensitivity of NTA dosimeters. It was anticipated that the results might assist in evaluating the needs of some licensees for a neutron dosimetry service.

This work was carried out in collaboration with the Radiation Protection Bureau (RPB) of the Department of National Health and Welfare. Selected workers from four oil-well logging companies were provided both with their "normal" NTA dosimeters for one month periods, and with CR-39 dosimeters to be worn for various periods for one month to one year.

The CR-39 dosimeter readings were compared with the sum of the NTA dosimeter readings for the corresponding period. Measurements with NTA emulsions were made by the RPB, which also handled all arrangements with the oil-well logging companies. Measurements with CR-39 dosimeters were made by AECL.

To assist in understanding the results, some of the properties and, in particular, the limitations of CR-39 and NTA dosimeters are discussed, along with the neutron energy spectra to be expected in oil-well logging.

2. CHARACTERISTICS OF RADIATION EXPOSURES IN OIL-WELL LOGGING

Oil-well logging workers can receive neutron doses from radioactive sources used in the ends of long, tubular probes that are lowered into well-holes. These sources are typically $^{241}\text{Am-Be}$ or ^{252}Cf , and have neutron outputs of the order of 5×10^7 neutrons/second. The neutron dose equivalent (DE) rate at 1 metre from an $^{241}\text{Am-Be}$ source of 5×10^7 neutrons/s is about 540 $\mu\text{Sv/h}$. Sources are normally stored in hydrogenous shielding and usually inserted into the probe only when the latter is about to be used. They are often handled on the end of a threaded rod, 1 to 1.5 metres long. The most likely exposure is to the worker who moves the source from its shielding and installs it in the unshielded probe. If this manoeuvre is not done close to the well, further exposures may be received while the probe is being transported.

Because of the relatively low output of the source and the short times during which people are likely to be exposed to it, most significant exposures will probably be from sources at no more than 1 or 2 metres from

the body. In these circumstances, a large fraction of the dose will be from direct neutrons rather than from those scattered from the ground, and these direct neutrons will have a spectrum not very different from that measured under laboratory conditions. A measured spectrum from an ^{241}Am -Be source is shown in Figure 1. Although in past years there have been considerable variations in such measured neutron spectra there is now reasonable agreement (both among measurements in various laboratories and between measured and calculated spectra) for that part of the spectrum above 1 MeV. At lower energies the spectrum is more sensitive to the size of the americium particles and to the amount of scattering material and, for these and other reasons, different measurements sometimes give discordant results.

^{239}Pu -Be and ^{210}Po -Be sources, which are sometimes used for calibrating and testing dosimeters, have neutron spectra quite similar to ^{241}Am -Be, differing mainly in the part of the spectrum below 1 MeV. A comparison of all these spectra is given by Geiger and Van der Zwan [1].

The spectrum of spontaneous fission neutrons from ^{252}Cf - the most extensively measured and accurately known of all neutron spectra - is also shown in Figure 1. It has its maximum at 0.71 MeV and a mean energy of 2.13 MeV. The fraction of total dose equivalent that comes from neutrons of less than 1 MeV is 8% for the ^{241}Am -Be spectrum and 22% for ^{252}Cf .

These fractions were calculated from the spectra of Figure 1 and the published variation of dose equivalent per unit fluence with energy [2]. They are of interest because the energy threshold for detection with NTA emulsions is somewhere between 0.5 and 1 MeV.

Neutron sources used in logging probes also emit gamma radiation. For ^{241}Am -Be sources, this has two origins - gamma rays of 60 keV and lower from the americium and 4.4-MeV gamma rays from the interactions of Am alpha particles with Be. Normally most of the 60 keV radiation is absorbed in the steel capsule containing the source. While the 60 keV gamma dose outside this capsule depends strongly on the wall thickness, typically the dose contributions from the 60 keV and 4.4 MeV radiations are roughly equal and together provide 4 or 5% as much dose equivalent as the neutrons. For ^{252}Cf sources, gamma rays over a wide range of energies are emitted in the spontaneous fission process and from fission products that have accumulated in the source. Their dose equivalent is again about 5% of that of the neutrons.

Hence for neither of these neutron sources do the gamma rays provide an important additional hazard. This gamma radiation is much too weak to interfere with the readings of NTA dosimeters at typical dose levels recorded by workers. Their effects will not be considered further.

3. PROPERTIES OF NTA-EMULSION DOSIMETERS

The properties and treatment of nuclear track emulsions are well known [3-6]. The main properties that might affect the readings of this intercomparison are the variation of response with neutron energy and with direction relative to the emulsion surface, the fading of tracks over the period between exposure and processing and the effects of the procedures for deriving low DE's from very small numbers of tracks on the minimum reportable DE.

3.1 Variation of Response with Energy

A typical response of NTA emulsion [7], giving the number of tracks/cm² for 1 μ Sv of neutrons of various energies, is shown in Figure 2. The threshold energy, below which the emulsion is very insensitive, is shown at about 0.5 MeV, but may be as high as 1 MeV depending on the techniques used in developing and identifying tracks. The variation of response between 1 and 14 MeV, while far from ideal, is not a serious limitation in measuring DE's from well-logging sources. An NTA dosimeter having the response shown in Figure 2, and that is calibrated to read ²⁴¹Am-Be DE's correctly would read about 25% low for ²⁵²Cf neutrons. This is calculated from the data of Figures 1 and 2 and the relation between fluence and DE [2] and is in reasonable agreement with a direct measurement by Bartlett et al. [8].

3.2 Angular Dependence

The angular dependence of the sensitivity of NTA emulsions varies with neutron energy in a rather complex way and also varies with the effective "radiator" i.e. any hydrogenous material in the dosimeter from which recoil protons can reach the emulsion. The most comprehensive measurements are those of Kathren et al. [9]. At energies above 3 MeV, the maximum sensitivity occurs for normal incidence and varies by a factor of 2 or 3 at other angles. A more important angular effect, for any neutron dosimeter worn on the body, is the shielding provided by the body for neutrons coming from various directions. For example, Po-Be neutrons coming through the abdomen of a "standard man" are attenuated by a factor of 7 [7] and the effect on ²⁵²Cf neutrons will be greater. At present this effect can only be removed by having several dosimeters around the body*, which is not usually considered worthwhile for measuring low-level doses. If the body is equally irradiated around a vertical axis (rotational symmetry), the reading of a dosimeter on the front of the body is about half of that for frontal irradiation.

* or by mounting a detector on the head

3.3 Fading

Fading is generally considered to be a serious drawback of emulsions. The fading rate increases rapidly as the temperature and relative humidity (RH) increase. It is more pronounced for low neutron energies and is affected to a considerable extent by the development conditions. As a result, fading rates reported by different experimenters vary widely. For the conditions under which NTA emulsions are processed at the RPB, Ghosh [10] found that 20% of the tracks from Pu-Be neutrons were lost after 4 weeks, at room temperature and at 45% RH. No measurements were made for other ambient conditions. Höfert and Piesch [6], using optimized development conditions, obtained similar results at room temperature but found 85% fading at 35°. Other experimenters generally have obtained higher fading rates. Kahle et al. [11] observed 55% fading in 2 weeks at 20°C and 50% RH. Becker [12] found that 35% of tracks from Po-Be neutrons were lost after 10 days at 22°C and 33% RH and 100% after 38 days. In one experiment at 100% RH, all tracks were lost in one week [13].

Whether or not fading is important over a 1-month period will depend on ambient conditions and may vary from summer to winter. A badge carried in a pocket will be at a temperature somewhere between ambient and body temperature (37°C) and will be at higher than ambient RH. If it is close to the latter temperature, fading will be much more severe. It was the experience of this intercomparison that badges were often not returned for processing for several weeks after the wearing period, so fading over a period greater than one month must be considered.

3.4 Statistics of Track Counting

For the processing procedures used at RPB, the sensitivity is approximately 1 track/mm² for 70 μSv of DE from Pu-Be neutrons*. The background is essentially zero. The counting procedure is to scan initially 1 mm². If there are less than 3 tracks, zero dose is reported; otherwise, an additional 3 mm² are scanned. To report a dose there must be 12 or more tracks in the 4 mm². Thus the minimum mean reportable DE is about 200 μSv. We here calculate the probability that a DE of 200 μSv is detected.

On the assumption of Poisson statistics the probability of getting exactly x tracks when the mean number is m is

$$P_x(m) = \frac{e^{-m} m^x}{x!},$$

* I am grateful to R. Bradley for providing the data on sensitivity and scanning procedure.

and the probability of getting x tracks or more is

$$K_x(m) = \sum_{n=x}^{\infty} P_n(m).$$

Then the probability of recording a 200 μSv DE by the above protocol, when the mean number of tracks/ mm^2 is 2.9 ($= 200/70$), is given by multiplying the probability that there are x tracks in the first mm^2 ($P_x(2.9)$ where $x \geq 3$) by the probability that there are $12-x$ tracks or more in the next 3 mm^2 ($K_{12-x}(8.7)$) and summing over all values of $x \geq 3$, namely,

$$\sum_{x=3}^{\infty} P_x(2.9) K_{12-x}(8.7)$$

which works out to 0.29. Thus there is a 71% chance that a 200 μSv DE will be missed. This chance is rapidly reduced as the DE increases. The probability of missing a 300 μSv DE is 26%.

For this intercomparison, the most important limitation of NTA emulsions is the inability to detect the very low doses that are usually received in oil well-logging. This is not exactly an inherent characteristic of the emulsion itself, but arises because it is impractical (because of time limitations) to scan the large emulsion area needed to give adequate counting statistics.

4. PROPERTIES OF CR-39 DAMAGE-TRACK DOSIMETERS

The general properties of damage track dosimeters for neutrons have recently been summarized by Tommasino [14], Harrison [15] and Cross [16]. The damage tracks of recoil protons and other charged particles produced in CR-39 plastic by neutrons remain for very long periods. They are enlarged to visible dimensions by chemical etching. Of the various damage-track materials, CR-39 has the unique property of being able to detect protons over a wide energy range and is much superior to other plastics as a neutron detector, both in sensitivity and in the range of neutron energies covered.

If proton tracks are enlarged by electro-chemical etching [17], they can be made large enough to be viewed in a microfiche reader with a magnification of 25 to 75 times. This permits up to 1 cm^2 of detector area to be viewed at one time. Large areas can thus be scanned in a short time and the statistics of counting small numbers of tracks from small doses are not a serious problem. On the other hand, unlike nuclear emulsions, unirradiated CR-39 has a significant background and variations in this background provide the limitation on the minimum detectable dose. The important characteristics of CR-39 are the energy response, the angular response, the absolute sensitivity and the background.

4.1 Variation of Response with Energy

The response to equal doses from neutrons of different energies depends on details of the etching process used. Tommasino [18] showed that a much better low-energy response could be obtained by using only electrochemical etching (ECE) rather than the combination of chemical etching and ECE that had been used previously [19]. With high temperature ECE, Cross et al. showed [20] that recoil protons down to 10 keV can be detected. However the etching conditions needed to detect as low an energy as this result in an undesirably high background in currently available CR-39. For personnel neutron dosimetry it is preferable to adopt etching conditions that reveal protons only down to about 50 keV but that give a lower background.

The resulting response to normally-incident neutrons is shown in Figure 2 [20]. It is reasonably flat between 70 keV and 6 MeV but drops off at higher energies. According to these results a CR-39 dosimeter calibrated to read DE correctly for ^{241}Am -Be neutrons would read 15% high in a ^{252}Cf spectrum. The variation of response with energy depends on the thickness of the polyethylene (or other hydrogenous "radiator" material) against the CR-39. If this thickness is less than the required amount, the response at high energies will suffer. The values of Figure 2 apply to a thickness of 1 mm.

4.2 Angular Dependence

An example of the variation in detector response with the angle between the neutrons and the normal to the detector surface is shown in Figure 3 [6]. Individuals exposed over a period of time in normal working conditions are not usually irradiated from a single direction*. If the detector is calibrated for 40° incidence it will read nearly correctly in a fluence that has rotational symmetry and will be high by a factor of 2 for normal incidence. While this variation is highly undesirable, it is less serious than the angular effect resulting from body shielding, mentioned in Section 3.2.

4.3 Sensitivity and Background

Both the sensitivity ($\text{tracks}\cdot\text{cm}^{-2}\cdot\mu\text{Sv}^{-1}$) and the background ($\text{tracks}/\text{cm}^2$ or equivalent μSv) of CR-39 vary a great deal with the etching and counting procedures used [15]. They may also be different for CR-39 from different manufacturers. The values quoted here apply to the procedures in use at CRNL, described in Section 5, and to CR-39 from American Acrylics.

* An exception may be persons working in front of a glove box that contains neutron sources. An oil-well logging worker who removes a neutron source from its shielding and inserts it in the probe (or "tool") is also likely to be irradiated mainly from the front.

The average sensitivity for the spectra of $^{241}\text{Am-Be}$ and ^{252}Cf neutrons can be calculated from the data of Figures 1 and 2. This gives $1.0 \text{ tracks}\cdot\text{cm}^{-2}\cdot\mu\text{Sv}^{-1}$ for ^{252}Cf and $0.87 \text{ tracks}\cdot\text{cm}^{-2}\cdot\mu\text{Sv}^{-1}$ for $^{241}\text{Am-Be}$. Direct measurements of the CR-39 detectors as used in the RPB badges, with calibrated ^{252}Cf and $^{239}\text{Pu-Be}$ sources, gave 0.76 and 0.70 $\text{tracks}\cdot\text{cm}^{-2}\cdot\mu\text{Sv}^{-1}$ respectively. These are the values used for determining DE's.

Since, in contrast to the case of NTA emulsions, it is practical to scan large areas of CR-39, the lower limit to the dose that can be detected with CR-39 is set not by counting statistics but by the background. More important than the absolute level of background is its variability. This background is the result of microscopic defects in the surface and volume of the plastic that are enlarged by the ECE process. It varies in CR-39 from different manufacturers, from one batch to another and, for CR-39 from some manufacturers, is very different on the two sides of a sheet.

The CR-39 used for this intercomparison has a background on the "good side" of typically $40\text{--}60 \text{ tracks}/\text{cm}^2$ which corresponds to 57 to 86 μSv of neutrons from $^{241}\text{Am-Be}$ *. Tracks are measured only on this side. Measured dose equivalents less than 30 μSv are not considered significant.

4.4 Fading of Tracks

For normal usage of CR-39 dosimeters fading is not usually important. It depends on temperature, but high relative humidities appear to have little effect. It presumably depends on the etching procedure used. Benton et al. [21], using only chemical etching, found no fading after 14 weeks at 22°C , but about 50% of the tracks disappeared after 7 weeks at 38°C . Hankins [22] found 12% fading during the first 3 months after a new sheet of CR-39 was received from the manufacturer, but no fading in 7 months afterwards. At CRNL no loss of 145-keV proton tracks was observed after 18 months. Storage of irradiated CR-39 at room temperature for 4 years before etching reduced the number of $\text{tracks}\cdot\text{cm}^{-2}\cdot\mu\text{Sv}^{-1}$ from ^{252}Cf neutrons by about 30%.

Fading is therefore not expected to have a significant effect on the present CR-39 measurements, unless some of the dosimeters were exposed to temperatures well above ambient. Further tests on fading over periods of a year or more would be desirable, since it is often practical to have badges worn for 6 months or more.

* CR-39 with a background less than half as large has recently become available but was not used in this work.

5. INTERCOMPARISON EXPERIMENT

A total of 63 CR-39 detectors were sent (in January 1985) to four oil-well logging companies (through the RPB), along with the regularly-issued NTA dosimeters and with instructions on how they were to be used. Each company was asked to select 3 employees who were judged most likely to receive neutron doses. Company A was asked to remove the CR-39 detector at the end of each monthly period for their regular NTA badge. Company B removed CR-39 badges only every second month, Company C after 6 months and Company D after a year. NTA dosimeters were replaced each month, as usual. A copy of the instructions sent to Company B is given as Appendix A.

The purpose of these various periods was to see if monthly DE's were being received that were below the limit of detection with CR-39 (30 μ Sv), but that could be detected when integrated over a longer period. Although the largest annual DE's were indeed recorded by detectors that were exposed over 6 or 12 months, the variation of DE's from one worker to another turned out to be so large that it was not possible to conclude that this occurred because of undetected monthly doses.

The damage-track detectors used were sheets of CR-39, 25 x 30 mm in area and 0.62 mm thick. Each surface was covered by a protective coating of polyethylene, 12 mg/cm² thick and the detectors were sealed in a polyethylene bag 10 mg/cm² thick. Detectors were identified by numbers scratched on the CR-39 surface and also marked in indelible ink on the outside of the bag. These detectors were placed in standard RPB badge holders, underneath the NTA film packet normally provided (Figure 4).

The NTA detectors were processed and read by the RPB in the standard way. The CR-39 detectors were processed at CRNL. After chemical etching in 28% KOH at 60°C for 1 hour they were electrochemically etched (in the same etchant) for 7 hours, using a field of 17 kV/cm (RMS) at 60 Hz. Tracks were projected on the screen of a microfiche reader (magnification 72 times) and counted by eye, normally over an area of 0.3 or 0.4 cm². Figure 5 shows the appearance of tracks produced by 3.8 mSv (380 mrem) of neutrons from ²⁵²Cf.

The CR-39 detectors were calibrated in RPB badges by exposures to 2 and 5 mSv from ²⁵²Cf and ²³⁹Pu-Be sources, in low-scattering geometry (Figure 6). The responses under these conditions were slightly lower than those derived from Figure 2, as given in Section 4.3. The neutron output of these sources was determined by comparison with that of the AECL standard Ra-Be source, which has been calibrated by NRC. This comparison was made using a long counter [25, 26]. The fluence at the dosimeters was converted to dose equivalent (calculated for a cylindrical phantom, 30 cm in diameter) using conversion factors given by Cross and Ing [2]. For ²⁵²Cf, this yields 1 neutron/cm² = 310 pSv while for ²⁴¹Am-Be, 1 neutron/cm² = 342 pSv.

6. RESULTS

The CR-39 dosimeter readings, for the various periods, are summarized in Table 1. Several of the badges were lost by their wearers, a few were misplaced by the companies and one set of 3 badges was apparently lost in the mail. In those instances where dosimeters were lost or not used, the annual dose given in Table 1 was obtained by multiplying the person's total recorded dose by the ratio of the total number of periods to the number of periods for which readings were obtained. Typically a few weeks elapsed between the end of a badge exposure period and receipt of the dosimeters. While most of the badges were issued to the same individuals throughout the year sets B-1 and B-3 were re-assigned to different people part way through the year, because of change of duties or for other reasons. Although these departures from the planned experiment are regrettable we have no reason to believe that they affect any of the conclusions of the tests.

In all cases, the individual monthly dose equivalents recorded by the NTA dosimeters were zero.

7. DISCUSSION

Of the monthly dose equivalents measured by CR-39, only one exceeded 200 μSv (20 mrem) and the DE's measured over longer periods were quite consistent with the assumption that few other monthly DE's exceeded this value. Since this is the minimum DE reported from the NTA dosimeter readings, it is not surprising that no DE's were recorded by the RPB badges.

It is clear that these workers often receive small doses, usually below 100 μSv /month. Because of the decreased sensitivity of the CR-39 detectors at large angles to the normal, and the effects of body shielding, some of the actual DE's received might be 2 or 3 times the recorded value.

Of the total recorded DE's over the year, only 2 out of 12 exceeded 1 mSv. This was a very small-scale test on a small fraction of those workers in the well-logging industry normally supplied with neutron badges and therefore deemed likely to be exposed to neutrons. If these workers are representative of the industry (they are supposed to be those most likely to be exposed) the neutron hazards in this industry are not very serious. Nevertheless the possibility of an unusually large exposure always exists and it would be unjustified to conclude that no significant neutron hazards exist in oil-well logging.

8. CONCLUSIONS

The oil-well logging workers on whom these tests were made often receive neutron dose equivalents between the lower limit of detectability of the CR-39 dosimeters used (30 μSv) and that of NTA emulsion dosimeters (200 μSv). CR-39 is more suitable than NTA emulsions for measuring such doses.

Over the whole year, the maximum measured dose equivalent was 1.54 mSv and only 2 of the 12 workers had recorded dose equivalents above 1.0 mSv. If the workers selected for this comparison are typical of those who handle neutron sources in this industry, neutron dose equivalents received in these operations are small compared with the gamma-ray doses received by many radiation workers in other industries.

TABLE 1: SUMMARY OF CR-39 READINGS (μSv). A1, A2, A3 are the 3 workers from Company A on whom the comparison was made.

<u>Company A</u>	<u>A1</u>	<u>A2</u>	<u>A3</u>
February	300	0	0
March	Lost	Lost	Lost
April	0	0	70
May	120	0	160
June	0	0	50
July	80	0	80
August	0	0	0
September	110	80	200
October	30	0	0
November	0	-	-
December	-	-	0
January	<u>0**</u>	<u>0**</u>	<u>0</u>
TOTAL	853 [†]	120 [†]	672 [†]
<u>Company B</u>	<u>B1</u>	<u>B2</u>	<u>B3</u>
February-March	0	0	0
April-May	30	0	Lost
June-July	50	120	Lost
August-September	0	30	30
October-November	40	30	0
December-January	<u>Lost</u>	<u>0</u>	<u>0</u>
TOTAL	144 [†]	180	45 [†]
<u>Company C</u>	<u>C1</u>	<u>C2</u>	<u>C3</u>
February-July	180	60	610
August-March*	<u>0</u>	<u>0</u>	<u>600</u>
TOTAL	180	60	1210
<u>Company D</u>	<u>D1</u>	<u>D2</u>	<u>D3</u>
February-January	50	1540	320

* Used for 7 1/2 months

** Not used

[†] Scaled to allow for missing readings, as described in Section 6.

REFERENCES

- [1] Geiger, K.W. and Van der Zwan, L. (1975). Radioactive neutron source spectra from $^9\text{Be}(\alpha, n)$ cross section data. Nuclear Inst. Meth. 131, 315-321.
- [2] Cross, W.G. and Ing, H. (1985). Conversion and quality factors relating neutron fluence and dosimetric quantities. Rad. Prot. Dosim. 10, 29-42.
- [3] Rosen, L. (1953). Nuclear emulsion techniques for the measurement of neutron energy spectra. Nucleonics 11, No. 9, 32-38 and 38-44.
- [4] White, R.S. (1960). Photographic plate detection, in "Fast Neutron Physics, Part I", (J.B. Marion and J.L. Fowler, eds.) Interscience, New York, pp. 297-334.
- [5] Barkas, W.H. (1963). "Nuclear Research Emulsions", Part I, Techniques and Theory", Academic Press, New York.
- [6] Höfert, M. and Piesch, E. (1985). Neutron dosimetry with nuclear emulsions. Rad. Prot. Dosim. 10, 189-195.
- [7] Piesch, E. (1963). On the dosimetry of fast neutrons with nuclear track films, Atompraxis 9, 179 (in German).
- [8] Bartlett, D.T., Bird, T.V. and Miles, I.C.H. (1980). The NRPB dosimeter. National Radiological Protection Board, Report No. 99, Berkeley, U.K.
- [9] Kathren, R.L., Prevo, C.T. and Block, S. (1965). Angular dependence of Eastman Type A (NTA) personnel monitoring film, Health Phys. 11, 1067-1069.
- [10] Ghosh, S.K. (1968). Calibration studies on the Kodak Type A nuclear emulsion film used in the neutron monitoring service. Report RPD-69, Radiation Protection Division, Department of National Health and Welfare, Ottawa.
- [11] Kahle, J.B., Arnett, E.N. and Meyer, C.T. (1969). Latent image fading in personnel monitoring neutron film, Health Phys. 17, 735-736.
- [12] Becker, K. (1973). Solid State Dosimetry, CRC Press, Cleveland, pp. 241-252.
- [13] Jasiac, J. and Musialowicz, T. (1973). Personnel fast neutron monitoring in Poland, in "Neutron Monitoring for Radiation Protection Purposes, Vol. II, IAEA, Vienna, pp. 191-197.
- [14] Tommasino, L. and Harrison, K.G. (1985). Damage track detectors for neutron dosimetry: I Registration and counting methods. Rad. Prot. Dosim. 10, 207-217.

- [15] Harrison, K.E. and Tommasino, L. (1985). Damage track detectors for neutron dosimetry: II Characteristics of different detection systems. Rad. Prot. Dosim. 10, 219-235.
- [16] Cross, W.G. (1985). Characteristics of track detectors for personnel neutron dosimetry, in "Proc. of 13th Int. Conf. on Solid State Nuclear Track Detectors", Rome.
- [17] Tommasino, L. (1970). Electrochemical etching of damage track detectors by H.V. pulse and sinusoidal waveforms, Proc. 7th Int. Colloq. on Corpuscular Photography and Solid State Nuclear Track Detectors, Barcelona.
- [18] Tommasino, L., Zapparoli, G., Spiezia, P., Griffith, R.V. and Espinosa, G. (1984). Different etching processes of damage track detectors for personnel neutron dosimetry. Nucl. Tracks 8, 335-340.
- [19] Griffith, R.V., Thorngate, J.H., Davidson, K.J., Rueppel, D.W., Fisher, J.C., Tommasino, L. and Zapparoli, G. (1981). Monoenergetic neutron response of selected etch plastics for personnel neutron dosimetry, Rad. Prot. Dosim. 1, 61-71.
- [20] Cross, W.G., Arneja, A. and Ing, H. (1985). The response of electrochemically-etched CR-39 to protons of 10 keV to 3 MeV, in "Proc. of 13th Int. Conf. on Solid State Nuclear Track Detectors", Rome.
- [21] Benton, E.V., Oswald, R.A., Frank, A.L. and Wheeler, R.V. (1981). Proton-recoil neutron dosimeter for personnel monitoring, Health Phys. 40, 801-809.
- [22] Hankins, D.E., Homann, S.G. and Davis, J.M. (1985). Personnel neutron dosimetry using an improved technique for electrochemical etching of CR-39 plastic, Health Phys. 49, 141.
- [23] Kluge, H. and Weise, K. (1982). The neutron spectrum of an ^{241}Am -Be(α ,n) source and the resulting fluence to dose equivalent conversion factors. Radiat. Prot. Dosim. 2, 85-93.
- [24] Piesch, E., Jasiac, J. and Urban, M. (1984). Makrofol and CR-39 track etch detectors as a supplement of a universal albedo neutron detector. Nuclear Tracks 8, 323-326.
- [25] Hanson, A.O. and McKibben, J.L. (1947). A neutron detector having uniform sensitivity from 10 keV to 3 MeV. Phys. Rev. 72, 673-677.
- [26] Allen, W.D. (1960). Flat Response Counters, in "Fast Neutron Physics Part I", (J.B. Marion and J.L. Fowler, eds.), Interscience, New York, pp. 361-386.

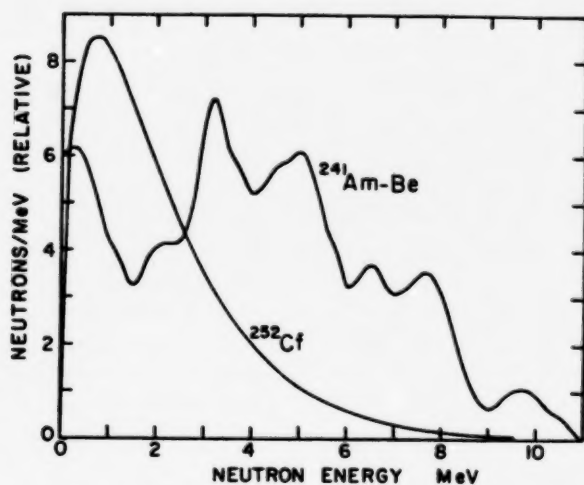


FIGURE 1 Spectra of neutrons from an ²⁴¹Am-Be and a ²⁵²Cf spontaneous fission source. The ²⁴¹Am-Be data are taken from measurements by Kluge and Weise [23]. The ²⁵²Cf curve is a theoretical fit to measurements by many experimenters.

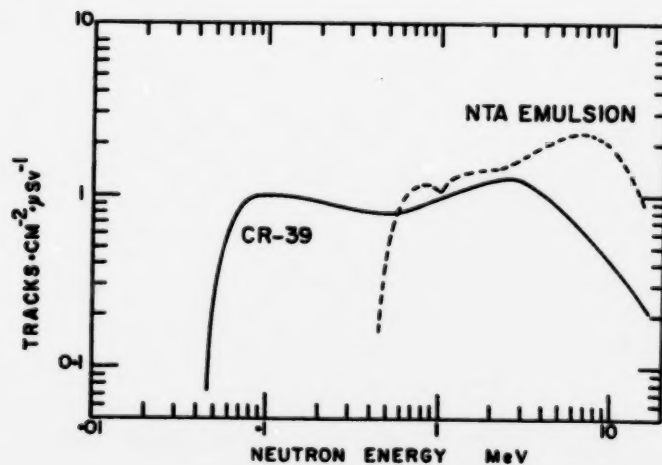


FIGURE 2 Variation of the response of NTA emulsion dosimeters and CR-39 damage track dosimeters as a function of neutron energy. The NTA response is taken from Piesch [7]. The CR-39 data are from Cross et al. [20] and apply to CR-39 covered by a 1 mm polyethylene radiator.

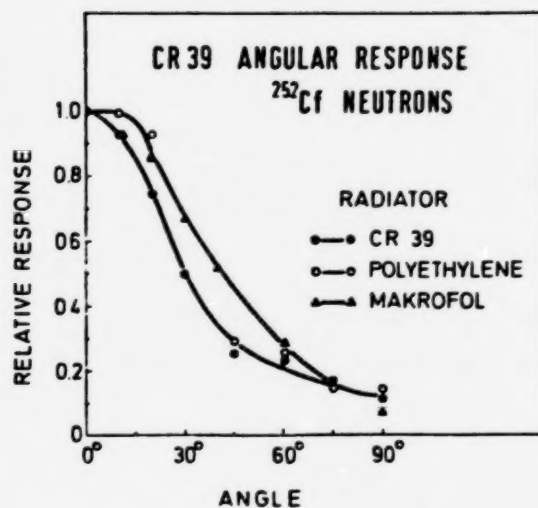


FIGURE 3 The variation of response of CR-39 dosimeters with the angle between the neutron direction and the normal to the surface. The data are from Piesch et al. [24].

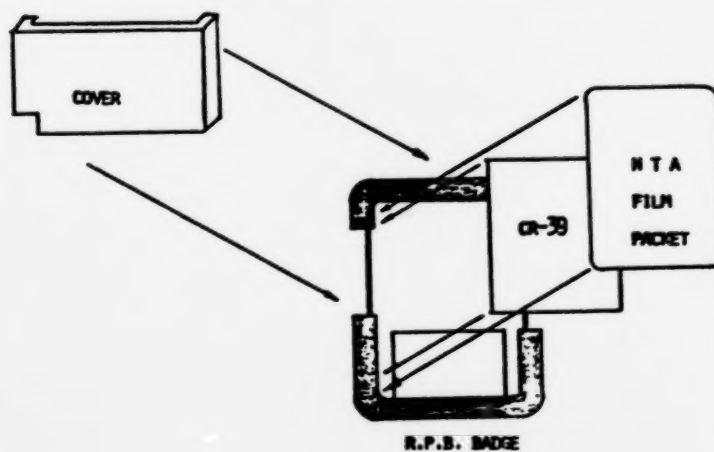


FIGURE 4 Radiation Protection Bureau badge with CR-39 and N.T.A. film detectors.



FIGURE 5 Appearance of damage tracks in CR-39 irradiated by 3.8 mSv ^{239}Pu -Be neutrons. This figure shows the actual size at which tracks are counted on the microfiche screen and covers about 1/12 of the area normally observed.

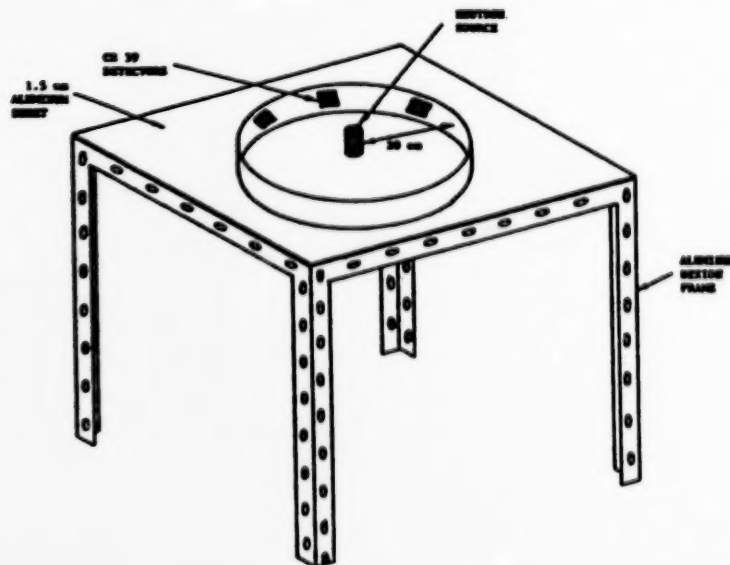


FIGURE 6 Detector calibration arrangement. The CR-39 detectors are mounted on the inside surface of a light Al cylinder.

APPENDIX A

SPECIAL NEUTRON DETECTORS

These special detectors are a new type of neutron detector and are to be given to three employees, selected by you, as part of an experiment to assess the accuracy with which doses from neutron sources are measured. This experiment will continue for 12 months. These detectors should be placed in badges along with the regular neutron films. Since neutron doses are normally very small, and often below the limit of detection, it would help this experiment if the special detectors were given to those employees who work around neutron sources most frequently.

While the regular neutron films should be continued to be changed in badges every month, the special detector should be changed only every two months. When changing detectors, the special detector should be put in the badge first and the regular neutron film placed on top of it. The side of the special detector with writing on it should be against the film. Badges should continue to be worn as usual with the clip next to the body. Special detectors should be returned to the Radiation Protection Bureau along with the regular films.

Each of the three selected employees should be assigned (for the 12-month period) one of the numbers written at the bottom of the special detectors and the Radiation Protection Bureau should be informed of the name corresponding to each number. There is another number in the upper right hand corner of each detector but this is of concern only to the Radiation Protection Bureau. The period for which each detector should be worn is also written on the detector.

If an employee to which one of these detectors is given leaves your employment during the 12-month period, or is reassigned to a job in which he is no longer likely to be working in the vicinity of neutron sources:

- (a) when badges are next changed the special detector should be given to another employee who works with neutron sources,
- (b) the Radiation Protection Bureau should be told the name of the employee who has ceased to wear the special detector and of the employee to which it has been given and the date on which the change was made.

If one of these special detectors is lost the Radiation Protection Bureau should be informed as soon as possible.